Innovative Power Hardware-in-the-Loop Testing Methods for Advanced Grid-Forming Inverters using Rapid Control Prototyping

Jonas Steffen, Fraunhofer IEE, Kassel, Germany, jonas.steffen@iee.fraunhofer.de
Tobias Erckrath, Fraunhofer IEE, Kassel, Germany, tobias.erckrath@iee.fraunhofer.de
Matthias Klee, Fraunhofer IEE, Kassel, Germany, matthias.klee@iee.fraunhofer.de
Fabian Schnabel, Fraunhofer IEE, Kassel, Germany, fabian.schnabel@iee.fraunhofer.de
Daniel Stracke, Fraunhofer IEE, Kassel, Germany, daniel.stracke@iee.fraunhofer.de
Prof. Dr. Marco Jung, Hochschule Bonn-Rhein-Sieg & Fraunhofer IEE, Germany, marco.jung@h-brs.de

Abstract

As the energy transition progresses and generation units become more decentralized, the grid-forming capabilities of inverters are gaining importance in the energy supply system. Although grid-forming inverters have been researched for some time, newly developed features add complexity to the testing framework. The design of the test grid is critical for ensuring accurate and reliable test results. This publication demonstrates how Rapid Control Prototyping (RCP) and Power Hardware-in-the-Loop (P-HiL) techniques create flexible test structures in the laboratory. It starts by presenting the RCP and P-HiL inverter used. Following that, it shows how the device merges both RCP and P-HiL functionalities and how the development environment supports rapid transition from concept to validation of innovative inverter control strategies. The focus then shifts to the grid-forming function under test, specifically the interaction between two grid-forming inverters. A microgrid serves as the test grid string, equipped with the RCP inverter and the P-HiL setup. The inverter uses a grid-forming control system to supply the test grid string, where real loads are connected. The P-HiL setup emulates a microgrid through a real-time computer, connected to the real test grid string via the P-HiL amplifier. This example highlights the synchronization process, load sharing, and the essential use of grid-forming features. The laboratory test implementation is shown with the RCP inverter and P-HiL amplifier. The flexible test setup is detailed, and the approach's advantages are visualized. An analysis of the test results is then performed, showcasing how the grid-forming control responds during load sharing and synchronization. Finally, the results and test setup are discussed, presenting the key findings from the test.

1 Motivation

The transition to renewable energy results in the loss of stability previously provided by large power plants [1]. To maintain this stability, grid-stabilizing systems must be integrated. According to the System Stability Roadmap from the German Federal Ministry for Economic Affairs and Climate Actions [2], inverters play a key role in this process. These inverters will be equipped with grid-forming functions to ensure supply security.

As part of this development, laboratory test procedures will also need to be expanded. A central question in this context is how to design an appropriate testing grid. The construction of such test grids can be very comprehensive and must be continuously adapted to the scenarios being tested. Methods such as Power-Hardware-in-the-Loop (P-HIL) are used to cover a number of use cases with less laboratory equipment compared to conventional tests [3, 4].

Additionally, Rapid Control Prototyping (RCP) significantly reduces the effort required for using the Device under Test (DUT). The combination of RCP and P-HiL techniques allows for the quick and efficient creation of many scenarios and use cases relevant to grid-forming systems.

Especially in the current phase, efficient testing methods are needed for research and development to successfully implement the System Stability Roadmap [2] in Germany.

2 Grid-Forming Control of Inverter

Grid-forming converters are characterized as a voltage source with impedance and therefore independent on an external synchronization voltage. In this context, they can serve as substitutes for synchronous machines and make a significant contribution to stable grid operation. The grid-forming capabilities allow a wide range of applications, from island grid operation to potential interconnected grid operation. This publication focuses on the parallel operation of grid-forming converters in island grid operation.[5]. **Figure 1** illustrates the structure of a control system for a grid-forming inverter and will be used in the following considerations [6].

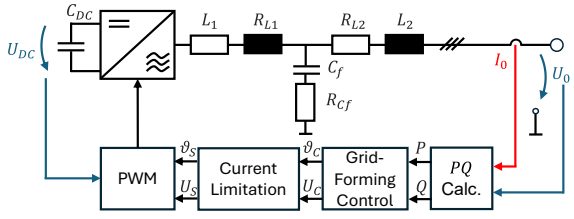


Figure 1 Schematic of a grid-forming inverter with the measurement and control circuit [6]

The structure of the grid-forming inverter shows the power electronic module, which is connected to a microgrid via a grid filter, in this case, an LCL filter. The control of the

inverter includes power calculation, the grid-forming control, current limitation, and pulse width modulation to drive the power electronic module. The measured values of grid current and voltage are captured.
The following sections will focus more closely on the grid-forming control and the current limitation essential for parallel operation.

2.1 Grid-forming control

Under the umbrella term of grid-forming control, various approaches can be found. Popular concepts include the virtual synchronous machine [7], or droop-based methods [8, 9]. In this context, a droop-based grid-forming control with two phase angle feedforwards are applied. This approach aims to enhance system stability and performance of the converter. The chosen method will allow for better integration of renewable energy sources and improve the overall reliability of the microgrid operation.
The presented grid-forming control includes a droop control and configurable first order low pass filters for inertia emulation [5, 6]. Furthermore, two phase angle feedforward paths can significantly increase the dynamics and prevents cross-coupling effects in resistive networks. **Figure 2** shows the control structure.

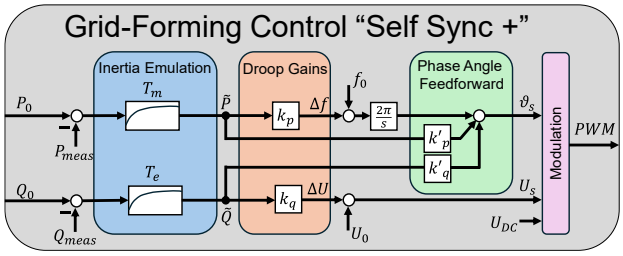


Figure 2 Droop based grid-forming control with phase angle feedforward [6]

The droops are set using the parameters k_p, and k_q. Additionally, the filter time constants T_m and T_e have an influence on the response of the amplitude and the phase angle of the provided voltages phasor according to changes of the connected grid. Properly tuning these parameters is vital for achieving a good performance of the grid-forming inverter, especially in scenarios where there are rapid changes in load or generation within microgrids.
As presented in [9], the droop-based grid-forming control demonstrates significantly better performance with a grid-forming controlled inverter compared to a conventional synchronous machine. For instance, in a load shedding experiment, the frequency overshoot caused by the load shedding was approximately 40-50% lower in the experimental tests with the grid-forming inverter. This improvement is attributed to the high damping capability provided by the angle feedforward. In terms of frequency stability, inverter-based systems equipped with this grid-forming control can effectively replace synchronous machines in terms of inertia and frequency control. Moreover, they significantly enhance the damping behavior of the system in response to frequency oscillations. [9].

2.2 Current Limitation

Additionally, the current must not exceed the device limits defined by the voltage setting characteristic and must be limited [10, 11]. Among various methods, three popular concepts are utilized: current limiters, virtual impedance, and voltage limiters. In this publication, a voltage limiter concept is chosen due to its effective current limitation performance and fault recovery capability [11]. The principle of the voltage phasor-based current limitation used in this approach is illustrated in **Figure 3**. This method ensures that the inverter can maintain operational integrity while responding to fault conditions, thereby enhancing overall system reliability and safety.

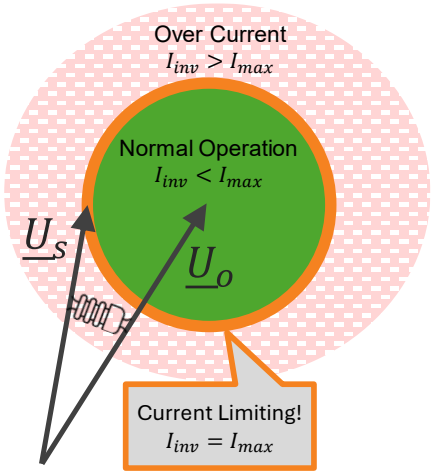


Figure 3 Voltage phasor-based current limitation [10]

The implicit current limitation is achieved by restricting the provided voltage phasor within a permissible area around the measured output voltage phasor. Specifically, the current limitation for the desired maximum current I_{max} can be accomplished by defining a circular permissible region for the provided voltage phasor $\underline{U}_s$ around the measured output voltage phasor $\underline{U}_o$. The maximum radius r is determined by the equation $U_{Z,max} = I_{max} \cdot Z_i$ where Z_i represente the inverter impedance [10]. This approach ensures that the current remains within safe operating limits, thereby protecting the inverter and the overall system from potential damage during transient conditions or fault events.

3 Power Hardware-in-the-Loop and Rapid Control Prototyping Systems

In this chapter, RCP and P-HiL will be examined in detail and the differences explained. RCP focuses on quickly developing and testing control algorithms in a simulated environment, allowing for fast iterations and adjustments. In contrast, P-HiL integrates actual systems with hardware and control components, enabling a more realistic assessment of system behavior under real-world conditions.
Additionally, this chapter will present an approach for the implementation and demonstration of grid-forming control

systems for inverters. This approach aims to showcase how these control strategies can be effectively tested and validated through both RCP and P-HiL techniques. By investigating these methods, their strengths and limitations become clear, ultimately leading to improved performance and reliability in grid-forming inverter applications.

3.1 Rapid Control Prototyping

With RCP, faster development of control algorithms is achieved. The focus is on evaluating functionality and early implementation of control algorithms on computational hardware. The intention is to initially use more extensive and faster computing hardware for RCP, in order to be more flexible in the implementation and to reduce programming effort. For RCP a powerful microcontroller is employed, allowing for a simplified workflow in programming. Automatic code generation from a model-based development environment is a very useful workflow with RCP. In device production a smaller and less expensive microcontroller will be used, which will be accompanied by more intensive code optimization. A powerful microcontroller is employed, allowing for a simplified workflow in programming. Commonly, automatic code generation from a model-based development environment is utilized.
The workflow with automatic code generation is a significant advantage of the RCP approach. This enables the developer of a concept to validate it in real-time on hardware with only rudimentary programming skills. These aspects facilitate the straightforward implementation of the control algorithm and allow for investigations in a real-time environment. In this publication, an extended approach to RCP for inverters is presented. The computational unit is enhanced with a power inverter module that imitating a programmable inverter setup that closely resembles real-world conditions, providing a more accurate testing and validation platform for the developed control strategies.
Figure 4 shows a block diagram of the setup of an RCP system.

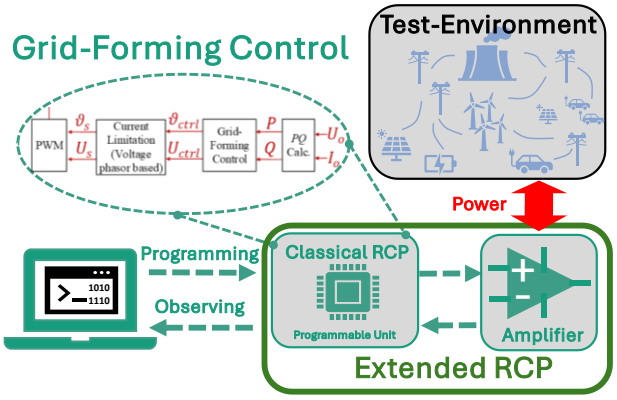


Figure 4 Block diagram of an RCP system extended with an inverter for comprehensive device under test interaction studies

The core component remains the computational unit, which is now connected to a test environment via an inverter. The extended RCP system can thus exchange not only small or digital signals but also power with the test environment.
In this case, the computational unit executes the previously presented grid-forming control along with current limitation and power calculation. Due to the flexible and often automatic programming, the user can easily switch between different model-based control approaches or make adjustments and directly examine the effects. The error-prone and lengthy translation of the model into code is handled by the workflow of the RCP system.
In this instance, the model-based development is carried out using MATLAB/Simulink, allowing for a seamless integration of control strategies and facilitating rapid prototyping and testing in a realistic environment. This approach enhances the overall efficiency of the development process and improves the reliability of the control algorithms being tested.

3.2 Power Hardware-in-the-Loop

P-HiL is fundamentally similar to an extended RCP system. It utilizes a highly capable computational unit to calculate complex systems in real-time. The main difference from the RCP approach is that the so-called real-time computer is designed to emulate larger, more complex systems, whereas the RCP focuses primarily on the control of a single device.
Additionally, the power interface, facilitated by an amplifier, is an essential part of the P-HiL system, as it translates the small signals from the emulated system into power. P-HiL enables the representation of the interaction between the test environment and the connected test device. Additional opens up the realization of complex test environments for individual devices without extending the test equipment.

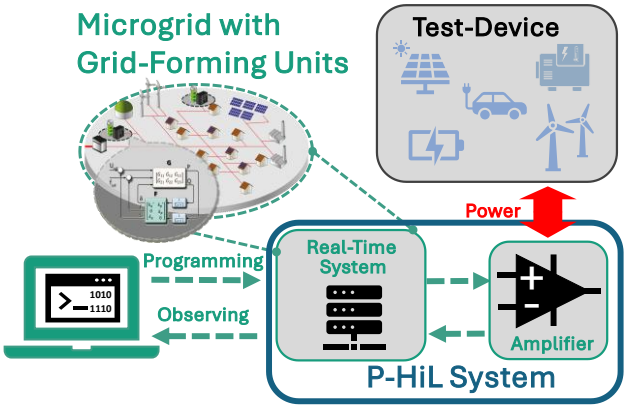


Figure 5 Block diagram of a P-HiL System with an emulated microgrid example

In **Figure 5**, the P-HiL setup is used to represent a small microgrid in real-time and to investigate the behavior of test devices under various grid scenarios. This allows for efficient testing and validation of control strategies in realistic conditions, providing valuable insights into system performance and stability.

3.3 Combining RCP and P-HiL for Grid-Forming Control Validation

The combination of the previously explained techniques enables the realization of flexible test setups. Once an RCP system is connected to a P-HiL system, various control approaches can be validated. In this case the RCP system serves as the test device, while the P-HiL system acts as the test environment.

The P-HiL system can execute different kinds of testing environments, in this case it emulates a microgrid. The RCP system, for this investigation, is equipped with the droop-based grid-forming control and the phasor-based current limitation. The RCP system functioning with a switch-mode amplifier like a realistic grid-tied inverter. This setup allows the investigation of the interaction between a grid-forming control and the emulated microgrid. Additionally, there is the possibility to integrate further real components through the power interface. Making the combination a very use full, flexible and reality-based laboratory validation platform.

4 Laboratory Setup for Grid-Forming Control Tests

A test setup was developed using P-HiL and RCP techniques for the laboratory investigation of the parallel operation of two grid-forming inverters in an island grid configuration. This setup involved the implementation of a P-HiL system, in which a simple microgrid was emulated. In this case, the microgrid consists of the interconnection of a (virtual) grid-forming inverter with a power rating of 34.5 kVA and a (virtual) passive load of 5 kW. Additionally, a (real) variable load is connected to the power interface, which will be switched in multiple stages between 0 kW and 80 kW throughout the laboratory experiment. The RCP system also has a power rating of 34.5 kVA, is equipped with the grid-forming control, and is connected to both the real load and the P-HIL system. For the experimental setup a real-time system from OPAL-RT was used. Additionally, two combined P-HiL amplifiers and RCP systems of the type RICOSO [12] from Fraunhofer IEE were used. The resulting test setup is shown in **Figure 6**. For the later analysis of the measurement data, two data loggers are used, which directly record the output voltage and current of the RCP system as well as the P-HiL system.

This setup allows the RCP inverter to effectively interact with the emulated microgrid. This enables the investigation of the dynamic responses of the grid-forming control under various load conditions and their impact on the stability of the island grid. Furthermore, potential improvements in control technology can be identified to optimize the performance and efficiency of the control system in parallel operation.

5 Test Execution and Analysis of Results

The test investigates the interaction between the two grid-forming inverters. Various load steps are performed, when adding the real and virtual loads the maximum load reaches 85 kW. This exceeds the applied inverter capacity of two times 34.5 kW, which is why the activation of current limitation is expected.

The results and test execution are shown in **Figure 7**. The upper graph displays the RMS voltage in percentage units, while the middle graph shows the RMS current in percentage units and the lower graph illustrates the frequency. The measurements from the P-HiL system are colored in orange, and the RCP inverter measurements are represented in blue. The dotted line at the current graph indicates the maximum allowed current.

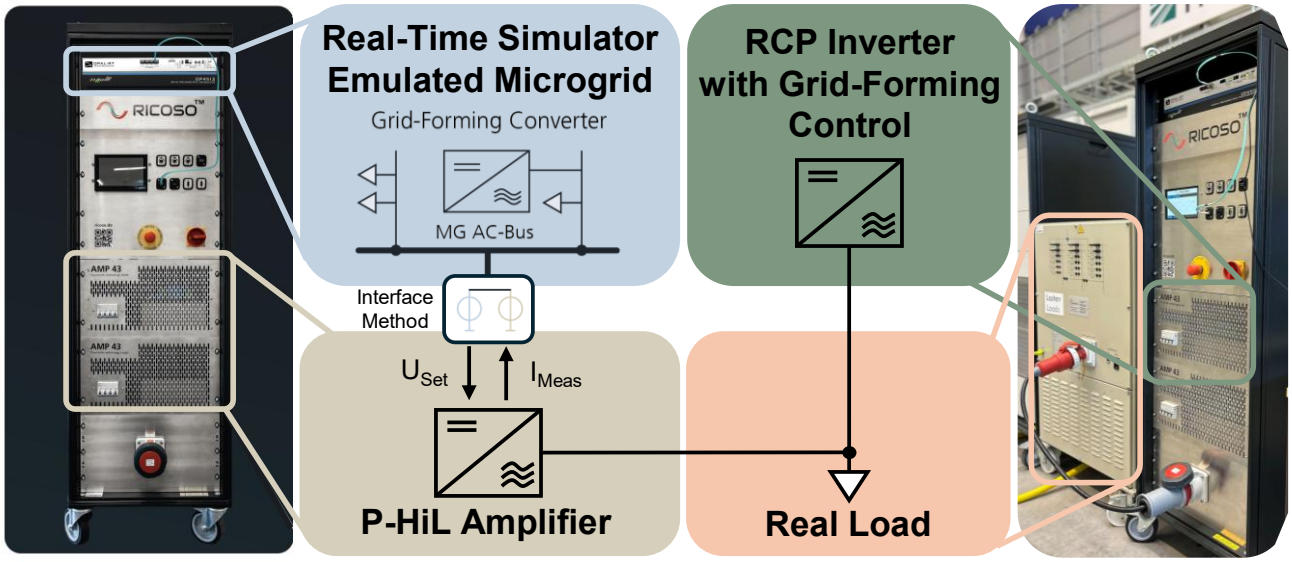


Figure 6 Test setup including a real variable load and two RICOSO systems

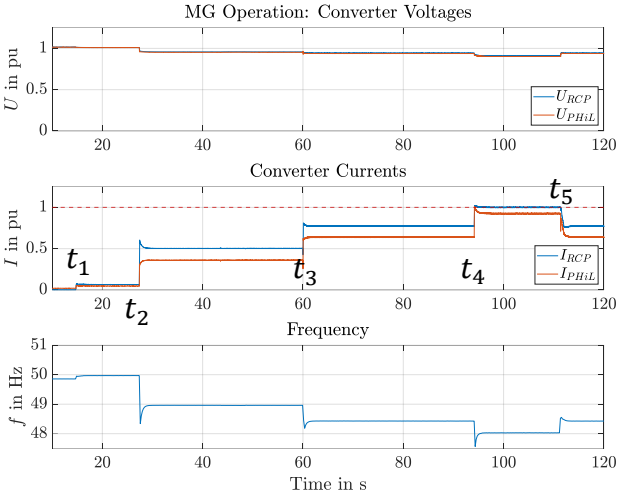


Figure 7 Diagram of the RMS voltage, RMS current, and frequency in the laboratory experiment for the parallel operation of grid-forming inverters.

At time step $t_0 = 0\ s$, the test begins with the running P-HiL system, but the RCP system is still off. At time step $t_1 = 10\ s$, the RCP system is activated and connected to the microgrid, resulting in a minor load exchange due to the droop control of the grid-forming control and the emulated microgrid load of 5 kW.
Furthermore, at $t_2 = 27\ s$ Figure 7 shows the reaction to an activation of an additional load of 30 kW. The grid-forming inverter quickly reacts, and a new stable operating point is established. Due to the internal emulated load, we observe an uneven load distribution. The frequency drops in accordance with the configured droop settings to 49 Hz. At $t_3 = 60\ s$, the real variable load is increased to 50 kW. As a result, another drop in frequency can be observed, followed by the establishment of a new stable operating point. At time step $t_4 = 94\ s$, the variable load is further increased to 80 kW. At this point, the requested load power exceeds the rated power of the inverters. In the current diagram, it can be observed that the current from the RCP system does not rise above 1 pu, as the inverter is operating in current limitation mode. It is also evident that the measurements of the P-HiL current do not reach 1 pu. However, it should be noted that the virtual grid-forming inverter still needs to supply the 5 kW load in the emulated environment and the measurements are only recorded at the amplifier of the P-HiL system. Within the emulated system, the inverter is in current limitation mode. The frequency drops to the lowest configured droop point of 48 Hz, and the voltage also decreases in response to the current limitation. The **Figure 8** shows an enlargement of the signals at time step $t_4 = 94\ s$ from the RCP system.
It can be observed that initially a clean sinusoidal current is fed in. Once the variable load is increased to 80 kW, the current shows values up to 1 pu. The current limitation function reliably ensures that the inverter does not exceed its rated current; however, additional harmonics are introduced in the process. The next load change, shown in Figure 7, occurs at time step $t_5 = 110\ s$. At this point, the variable load is reduced to 50 kW, and both inverters return to normal operation, restoring the load sharing as it was before the current limitation event.

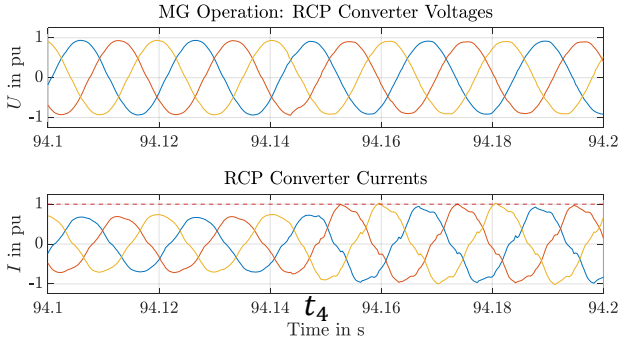


Figure 8 Diagram of the current and voltage measurement from the RCP system at time step $t_4 = 94.15\ s$

6 Conclusion

Initially, the grid-forming control was introduced, followed by the presentation of an appropriate current limitation function. The construction of an RCP system with a power interface was explained. Subsequently, the setup of Power Hardware in the Loop systems was discussed. The combination of these two systems was presented, followed by the test setup, which included an emulated microgrid, one real and one virtual grid-forming inverter, and the variable load. During the test execution, various load situations were considered, with a notable event being the parallel operation under current limitation conditions.
The combination of RCP and P-HiL techniques enables rapid validation of control concepts in a realistic environment. By allowing the emulation of various grid scenarios, it is possible to quickly switch between simple and complex test environments without the need to expand the laboratory with real hardware. The techniques presented facilitate the creation of flexible test environments that are specifically necessary for grid-forming inverters. Novel designs like the RICOSO system are multifunctional. The System is able to act as an RCP system with the internal processing unit and can be extended by a real-time computer to become a P-HiL System.
A simple microgrid was emulated, which will be elaborated in future investigations to include additional grid operating resources. Furthermore, it is planned to optimize the interface method of the P-HiL system for the use case in the upcoming tests. It is suspected that the harmonics in the case of current limitation are caused by the interface method. Further steps involve employing different grid-forming techniques and current limitation methods.

@ VDE Verlag

Acknowledgement
The authors would like to thank the German Federal Ministry for Economic Affairs and Climate Action as well as the Project Coordinator Jülich for funding the research project F-HiL_Reloaded (support code 03EI6104B) leading to this article.
Only the authors are responsible for the content of this publication.

7 References

[1] T. Ackermann, T. Prevost, V. Vittal, A. J. Roscoe, J. Matevosyan, and N. Miller, "Paving the Way: A Future Without Inertia Is Closer Than You Think," *IEEE Power and Energy Mag.*, vol. 15, no. 6, pp. 61–69, 2017, doi: 10.1109/MPE.2017.2729138.

[2] Federal Ministry for Economic Affairs and Climate Action (BMWK), "System Stability Roadmap: Roadmap for achieving the secure and robust operation of the future power supply system with 100% renewable energy sources," Berlin, Nov. 2023. Accessed: Sep. 28 2024. [Online]. Available: https://www.bmwk.de/Redaktion/EN/Publikationen/Energie/system-stability-roadmap.pdf?__blob=publicationFile&v=5

[3] R. Brandl *et al.,* "Power Hardware-in-the-Loop Testbed for High Frequency Interdependency Issues of Inverter-Based Generation," *Proc. of the 25th International Conference on Electricity Distribution (CIRED 2019)*, 2019, doi: 10.34890/692.

[4] C. S. Edrington, M. Steurer, J. Langston, T. El-Mezyani, and K. Schoder, "Role of Power Hardware in the Loop in Modeling and Simulation for Experimentation in Power and Energy Systems," *Proc. IEEE*, vol. 103, no. 12, pp. 2401–2409, 2015, doi: 10.1109/JPROC.2015.2460676.

[5] P. Unruh, M. Nuschke, P. Strauß, and F. Welck, "Overview on Grid-Forming Inverter Control Methods," *Energies*, vol. 13, no. 10, p. 2589, 2020, doi: 10.3390/en13102589.

[6] T. Guhna, D. Stracke, M. Klee, F. Schnabel, A. Seibel, and M. Jung, "Hardware and Software Concept for Distributed Grid-Forming Inverters in Microgrids," in *2021 23rd European Conference on Power Electronics and Applications (EPE'21 ECCE Europe)*, Ghent, Belgium, 2021, P.1-P.10.

[7] R. Hesse, D. Turschner, and H.-P. Beck, "Micro grid stabilization using the Virtual Synchronous Machine (VISMA)," *RE&PQJ*, vol. 7, no. 1, 2009, doi: 10.24084/repqj07.472.

[8] X. Wang, F. Blaabjerg, and Z. Chen, "An improved design of virtual output impedance loop for droop-controlled parallel three-phase voltage source inverters," in *2012 IEEE Energy Conversion Congress and Exposition (ECCE)*, Raleigh, NC, USA, 2012, pp. 2466–2473.

[9] P. Unruh, R. Brand, A. Seibel, and M. Jung, "Enhanced Grid-Forming Inverters in Future Power Grids," in *2018 20th European Conference on Power Electronics and Applications (EPE'18 ECCE Europe)*, 2018, pp. 1–10.

[10] T. Erckrath, P. Unruh, and M. Jung, "Voltage Phasor Based Current Limiting for Grid-Forming Converters," in *2022 IEEE Energy Conversion Congress and Exposition (ECCE)*, Detroit, MI, USA, 2022, pp. 1–8.

[11] B. Fan, T. Liu, F. Zhao, H. Wu, and X. Wang, "A Review of Current-Limiting Control of Grid-Forming Inverters Under Symmetrical Disturbances," *IEEE Open J. Power Electron.*, vol. 3, pp. 955–969, 2022, doi: 10.1109/OJPEL.2022.3227507.

[12] Fraunhofer IEE, *RICOSO Webside.* [Online]. Available: http://ricoso.de/ (accessed: Jan. 31 2025).

@ VDE Verlag